Appendix IV: Lead-Cooled Fast Reactor

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LEAD-COOLED FAST REACTOR (LFR)

The LFR development effort is formulated to provide a new generation reactor and fuel cycle technology meeting U.S. safety, security, environmental and non-proliferation requirements, demonstrated in the U.S. and deployable commercially in the U.S. and abroad. The vision and mission for the LFR program are as follows:

Vision
The vision of the LFR program is the future commercial deployment of advanced small reactors (10-100MWe), which are highly proliferation resistant (with no on-site storage or handling of fuel), employ sealed reactor cores with lifetimes of up to 30 years, are economic and simple to operate, and are deployable virtually anywhere in the world.

Mission
The mission of the LFR program is to research, design, develop and demonstrate an advanced small reactor that is safe, secure, transportable and highly proliferation resistant, such that the concept is prepared for commercialization by 2025.

The schedule proposed is illustrated in Figure 1. If there is sufficient interest in an earlier demonstration than that identified in the current GEN IV schedule, then a Critical Decision-driven schedule for a demonstration project can be prepared. However, the plan described in this appendix is limited to a 10-year duration as part of the longer-term schedule reflected in Figure 1.

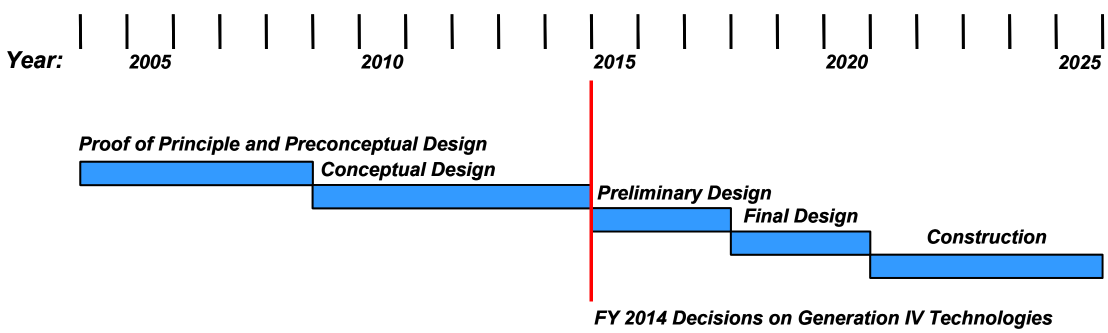

Figure 1 LFR Timeline

Envisioned deployment applications include remote locations that are ill-served by currently available power systems, locations in developing countries with little or no supporting infrastructure, and possibly (if competitive economics can be attained) new energy products from merchant plants in developed countries. The envisioned reactor system will utilize the advantages of lead or lead-bismuth eutectic (LBE) coolant to achieve relatively high core outlet temperatures, which can allow realization of relatively high system efficiency and/or production of hydrogen using high-temperature processes. Efficiency improvements with either lead or LBE might be obtained through the use of an innovative energy conversion scheme, such as a Brayton conversion cycle that utilizes supercritical CO_2 as a working fluid. The reactor will accommodate a closed fuel cycle while ensuring substantial proliferation resistance by limiting access to fuel and associated fuel handling infrastructure.

Specifics of the system will be determined through design and evaluation. But potential attributes include the following:

- A small, factory-built turnkey plant, designed to meet market opportunities for electricity production on small grids, and for developing countries that may not wish to deploy an indigenous fuel cycle infrastructure to support their nuclear energy systems
- Lead or LBE coolant
- A sealed vessel and/or cassette core with 30-year lifetime
- A natural circulation primary, with attendant advantages for maintenance and safe operation
- Enhanced thermo-structural feedbacks that impart passive safety and enable autonomous load following
- Potential options for energy conversion through supercritical CO_2, supercritical steam, or high-temperature hydrogen production
- License-by-test leading to certification in a manner similar to that used by the U.S. Federal Aviation Administration for certifying airliners
- Simple design and automated operations with advanced instrumentation and controls

The characteristics of a reference plant design plant and the timing and strategy for demonstration will be determined on the basis of the products of research. Major parameters such as power level, operating temperature, coolant (lead/LBE), and demonstration requirements will be determined as a reference design is established through research. Because the economic, proliferation resistance, and inherent safety characteristics of this system are essential to warrant its further development, the design and operating principles to achieve beneficial performance must be established early in the program. Principles of autonomous load following and natural circulation primary heat removal should also be addressed early in the development program because their incorporation into modular plants enhance the attractiveness for certain deployments. Brayton cycle technology (e.g., supercritical CO_2 as secondary working fluid) must be evaluated to determine whether it is feasible and attractive for LFR implementation. In addition, a license-by-test approach must be established early in the program to provide guidance to program and technology development tasks. For these reasons several system design options will be developed along with supporting component and sub-system descriptions for use in discussions with the U.S. NRC, which will be necessary to formulate an accepted approach to licensing.

Some of the technology advances required to realize the LFR will be pursued, in part or in total, in other parts of the Generation IV program (e.g., innovative energy conversion, hydrogen production technology, and high-temperature, radiation resistant materials) or in the Advanced Fuel Cycle Initiative (e.g., fuel designs and cladding materials).

Therefore, the LFR program will necessarily be conducted in a coordinated manner as part of the overall nuclear energy development program.

1 DESIGN AND EVALUATION

The goal of the system design and evaluation studies is to develop and establish a system design, based upon results of deployment studies and evaluation, through selected R&D and system demonstration. Therefore, system design and evaluation is logically divided into the two major tasks: 1) Design Evaluation and Optimization, and 2) Deployment Studies and Evaluation. Coordination with international partners is critical to optimizing the resources available for LFR development.

1.1 Design Evaluation and Optimization

Associated sub-activities are identified and described below.

1.1.1 System Design

Objectives:

- Define a reference point design for pre-conceptual studies
- Evaluate design options, including those necessary for features such as long-life core usage and autonomous load following
- Prepare a conceptual design
- Initiate a preliminary design effort, contingent upon DOE priorities and funding

System concepts will be identified and evaluated to serve as a basis for early design studies and R&D activities. As soon as is appropriate, a reference system point design will be identified, which will serve as the basis for focusing subsequent design and evaluation. Specific types of activities include the following:

- Formulation of design criteria
- Evaluation of design options against the design criteria
- Preparation of Conceptual Design package
- Final design of demonstration prototypes

1.1.2 Safety Evaluation

Objectives:

- Establish safety-related design criteria
- Evaluate design options against safety-related design criteria
- Formulate and perform additional analyses or experiments as required to establish design limits or to asses design characteristics

System component concepts and the system design will be continually evaluated for safety-related performance. The assurance of reliable and effective thermo-structural reactivity feedback is key to the desired passive safety/passive load following design strategy and will require coordinated neutronics/thermal-hydraulics/structural design of the core. As specific safety issues with relatively large uncertainties are identified, selected safety testing will be formulated and conducted. For example, such testing might include preliminary testing of mixed nitride fuel under severe upset in-core temperature conditions to assess the consequences of such accidents.

1.1.3 Lead/LBE Technology

Objectives:

- Determine technical requirements for ensuring suitable operation of a reactor primary heat removal system using lead or LBE
- Establish industrially-usable techniques for controlling chemistry and measuring flow of lead/LBE coolant

The properties of heavy metal coolants such as lead or lead-bismuth eutectic (LBE) provide an opportunity to design a fast reactor with excellent passive safety characteristics and safety margin. However, exploiting this opportunity will require that the technology to use such coolants be managed. Therefore, necessary R&D activities are included for the following:

- Natural circulation characteristics of lead/LBE
- Oxygen sensor technology
- Oxygen control techniques and instrumentation
- Flow measurement and monitoring techniques and instrumentation
- Off-normal characteristics for flow and oxygen content
- Strategies and means for control of Po-210, an activation product of Bi
- Effects of radiation on coolant technology, materials and instrumentation

Materials compatibility and performance in lead/LBE are an important aspect of lead/LBE technology. Although these specific concerns are addressed separately in the following subsection on materials, it should be noted that the materials testing activities will necessarily be closely coupled with the lead/LBE technology development activities.

1.1.4 Heat Transfer and Fluid Flow

Objectives:

- Determine the heat transfer characteristics of lead and LBE to reduce uncertainty in safety and design calculations
- Establish a set of reference thermophysical properties for lead/LBE.

The heat removal from the fuel pin lattice (and also across intermediate heat exchanger tube bundles) uses natural or low-speed forced circulation through an open lattice of ductless assemblies. Heat transfer correlations, pressure drop correlations, pressure drop form factors for plenum flows and transitions, and flow redistribution patterns need to be developed as a function of geometry and pin linear heat rate both in the lattice and in the overall reactor flow circuit. The effects of grid spacers, deposits, and clad aging will have to be understood to support the long-term viability of natural circulation. This requires the availability of loops with a height useful for natural circulation, and also large-scale plenum flow facilities. Thermophysical properties of lead and/or lead-bismuth eutectic, and their dependence on oxygen levels, will be assessed and a reference set of properties established.

1.1.5 Reactor Engineering

Objectives:

- Develop design concepts that allow innovative features of the LFR
- Address feasibility issues such as fuel handling during on-site reactor/core change-out and in-service integrity verification

The modularity envisioned for the small, modular LFR and the unique aspects of reactor design for lead/LBE coolant will require an associated set of R&D activities, which will inform the design activities described above. For example, reactor internals support techniques and refueling, core positioning, and clamping strategies are issues for investigation because the internals and the fuel will float (unless restrained) in the dense coolant. Other development will include in-service inspection technologies and structural support of the reactor vessel, containing dense lead/LBE coolant, for seismic isolation and sloshing suppression. Additional reactor engineering R&D needs will likely be identified through the design and evaluation process.

1.2 Deployment Studies and Evaluation

The deployments that motivate the development of small modular reactors with the attributes targeted in this program are somewhat different from those of baseload electricity generation plants in a developed country. Therefore, aspects of economics, proliferation resistance, and licensing will likely be unique.

1.2.1 Economic Studies

- Establishment of a set of requirements for LFR economic performance
- Evaluation of design options for impact on economic performance

The economic environment that will drive the selection and use of a small modular LFR is expected to be different than for a large base-load plant, although base-load application in a developing country is retained as a possibility. Therefore, the economic factors associated with energy needs in developing countries or remote locations or for production of specialized energy products (e.g., hydrogen or hydrogen fuel cells) will be considered and evaluated for implications for the LFR. For example, evaluations are needed to determine quantify the economies that can be achieved by plant simplification, factory fabrication and assembly, and reduced footprint. The contribution from factory assembly at a much higher rate of production than large plants must be established in order to achieve competitive economics for the LFR. This will require investigation of factory design and production plans that can be fed back into design. LFR system performance requirements and design criteria will be identified for incorporation into the R&D goals of this program.

1.2.2 Proliferation Assessment

- Establishment of a set of principles for LFR proliferation resistance
- Evaluation of design options for impact on proliferation resistance

Because envisioned deployments for the LFR system include developing countries without current nuclear energy capabilities and remote locations that are far removed from supporting infrastructure, proliferation characteristics will require appropriate evaluation. Potential features of the LFR system include whole-core cartridge assemblies, which render access to fuel difficult or impossible, and eliminate the need for indigenous fuel services. Replacement of the entire reactor assembly with the fuel sealed inside is also a possibility that needs further investigation to determine the impacts such an approach has on design. However, the features that will be required to provide proliferation resistance and their efficacy must be evaluated, with the results informing the design process through appropriately formulated design criteria. This task will be closely coordinated with the GIF Proliferation and Physical Protection Working Group.

1.2.3 Licensing Approach

- Establishment of an LFR licensing strategy

A *license-by-test* approach is proposed for the LFR, which will utilize demonstration and testing with prototype units to provide data and confirmation of safety-related behavior and characteristics. The approach envisioned will address new methods of production and installation and consider standard plant certification from an approved testing program that includes a broad range of safety tests. Establishing and securing acceptance of such an approach will require development of the licensing process, and considerable early interaction with and input from regulatory and industry representatives.

2 MATERIALS

The objectives of the LFR materials research are to identify materials of construction for a demonstration prototype reactor and for a commercially deployable design, to develop corrosion control strategies, and to provide the data required to support materials qualification in licensed reactor facilities. These objectives require the program to address significant materials and coolant technology challenges. These issues include:

- Corrosion challenges related to the use of lead coolants
- Monitoring and control of coolant flow and chemistry

- The need for a simple, low-maintenance design with high inherent safety to achieve high component reliability requirements
- High radiation damage performance requirements related to the fast neutron spectrum and the very long life time requirements
- Long cladding lifetime required for the long core life of the reactor
- High-temperature materials performance requirements

The viability R&D which is the focus of the first several years of this program will not develop the entire engineering database, the engineering code case, or complete fabrication technique procedures, but will establish the primary candidate materials for further testing.

2.1 Survey and Selection of Candidate Cladding, Control, Duct, and Structural Materials-Mechanical and Corrosion Performance

Objectives:

- Identification of materials of construction that make the LFR concept feasible
- Early indication of materials behavior or characteristics that limit in-service conditions for LFR components

Candidate materials have been and will be continue to be identified based on literature survey and investigation of materials usage in industrial applications. Materials will be screened for adequate mechanical performance, corrosion resistance, and fabricability. Testing will take place over the range of temperatures, flows, and stresses expected in the LFR system. The materials of interest may be different for the lower temperature (550°C) and higher temperature (800°C) versions. For long-life cores, there is a strong need for accelerated materials testing coupled with benchmarked materials performance modeling to reliably predict lifetime performance. For cladding, compatibility with lead/LBE on the coolant side and metal or nitride fuel on the fuel side is required.

2.2 Lead/LBE Corrosion Testing of Candidate Cladding, Control, Duct, and Structural Materials

Objectives:

- Acquire corrosion performance and properties data for candidate materials of construction for support of conceptual and preliminary design efforts
- Determine corrosion-based limiting conditions of operation for selected materials

Lead/LBE corrosion properties of candidate materials will be investigated under LFR-relevant coolant conditions of chemistry, flow, and temperature. These tests will be conducted using various techniques and facilities, but most notably by using the DELTA loop at LANL. Therefore, the testing will coordinated in a long-term experimental program that includes development of Lead/LBE technology using the loop facility.

2.3 Irradiation Testing of Candidate Cladding, Control, Duct, and Structural Materials

Objectives:

- Acquire irradiation performance and properties data for candidate materials of construction for support of conceptual and preliminary design efforts
- Determine irradiation properties-based limiting conditions of operation for selected materials

Candidate materials will be irradiated under fast spectrum conditions at LFR relevant temperatures and stresses. Following irradiation, materials will be evaluated to determine mechanical properties, microstructural evolution, and corrosion resistance. These efforts will be performed as part of a larger materials development and assessment activity within the Generation IV program. As part of the LFR-specific workscope, screening studies may be performed using high-energy ion beams to induce irradiation-damage microstructures in samples that can be characterized and tested for corrosion properties.

2.4 High-Temperature Design Methods

Design methods will be evaluated and extended to cover the temperature and stress regime of the LFR. Developing high temperature design methods is expected to be addressed as Crosscutting Materials R&D.

2.5 Materials Modeling

Objectives:

- Develop mechanistic models of phenomena that control materials behavior in LFR environments
- Use mechanistic materials behavior models to better understand the phenomena that control materials behavior in LFR environments, for the purpose of informing design efforts

Advanced, mechanistically-based models for irradiation performance and corrosion of materials in Lead/LBE will be developed. Such development is expected to be a crosscutting activity to be addressed as Crosscutting Materials R&D.

3 ENERGY CONVERSION

R&D activity will be performed to support the LFR balance of plant in the areas of supercritical CO_2 Brayton cycle for energy conversion, Ca-Br water cracking for hydrogen production, and heat exchanger design. These activities are expected to take place as part of an effort on Crosscutting Energy Products R&D.

3.1 Development of Supercritical CO_2 Brayton Cycles

Objective:

- Establish applicability of SCO_2 Brayton cycle technology to LFR operating conditions and the suitability of the technology for the deployments envisioned for the LFR

R&D activity will be performed to support the LFR balance of plant for coupling to a Supercritical CO_2 Brayton cycle. This activity is expected to take place as part of an effort on Crosscutting Energy Products R&D. However, LFR-specific requirements and implications for application of the technology to the LFR will be addressed as part of the LFR program.

3.2 Development of Ca-Br Water Cracking Cycles

Objective:

- Establish the technical basis for coupling supercritical carbon dioxide Brayton cycles and/or calcium-bromide (Ca-Br) thermo-chemical water cracking cycles to lead-cooled fast reactors

R&D activity will be performed to support the LFR balance of plant for coupling to a Ca-Br water cracking process for hydrogen production. This activity is expected to take place as part of an effort on Crosscutting Energy Products R&D.

3.3 Development of Heat Exchangers for Coupling to Energy Conversion Systems

Objective:

- Establish LFR-specific requirements and considerations for heat exchangers to be coupled with various energy conversion systems

For LFR related process heat applications, an intermediate heat transport loop is needed to isolate the reactor from the energy converter for both safety assurance and product purity. A heat exchanger materials screening is needed for potential intermediate loop fluids, including molten salts, He, CO_2 and steam. For interfacing with thermo-chemical water cracking, the chemical plant fluid is HBr plus steam at 750ºC and low pressure. For interfacing with turbo-machinery, the working fluid options are supercritical CO_2 or superheated or supercritical steam. The interface issues will be handled as part of this LFR R&D plan. Materials will be identified and tested for adequate mechanical and corrosion resistance in high temperature primary coolant and thermo-chemical water cracking working fluids.

4 FUEL AND FUEL CYCLE

The goals of the fuel and fuel cycle R&D are to establish fuel fabrication techniques, develop the fuel properties data base, establish adequate performance for fresh and recycled fuels, and to establish recycle technology. The near-term research in this effort will include defining fuel performance requirements, fuels design and definition, compatibility testing of fuel and cladding and their compatibility with lead coolant, selection of a reference fuel form and cladding material, cladding and coolant materials testing, and fuel design for long life. Established fuel concepts (or minor variants thereof), such as nitride pellet or metallic rod-type fuel, will be considered first, but innovative fuel concepts will be considered as necessary. The tasks described below are limited to those necessary to determine a reference fuel concept and design and to establish concept feasibility. These efforts, as well as the detailed testing and development efforts that are necessarily part of a longer-term development and demonstration program but are not addressed in this 10-year plan, will be performed in close association with ongoing fuel development efforts in the Advanced Fuel Cycle Initiative.

4.1 Fuel Selection, Requirements and Qualification

Objective:

- Determine the requirements for LFR fuel, consistent with a 30-yr core lifetime
- Establish feasible reference and alternative fuel designs
- Develop a strategy and plan for qualifying LFR fuel, consistent with the

Initial fuels work will be directed toward developing detailed fuel performance requirements based on the needs identified in the initial reactor design. These requirements will be updated as the design evolves from pre-conceptual to conceptual stages. As these requirements take form, reference and alternative fuel concepts will be selected based on literature assessment and experience. In addition, a fuel qualification plan will be developed to address the needs of the reactor design and its safety and licensing approach. This plan will be complicated by limited availability of fast-spectrum testing facilities, so the start-up strategy for a demonstration plant will likely include provision for fuel performance verification and surveillance.

4.2 Fuel Design for Long Lifetime Cores

Objective:

- Develop a fuel design with prospect for allowing long core lifetime

The utilization of a sealed core with long lifetime is central to the LFR concept. However, the extended time at temperature will provide some technical challenges to fuel design that must be considered. Fortunately, previous experience with fast reactor fuels has provided some insight into factors that might mitigate life-limiting phenomena at the core conditions expected in the LFR (which include, nominally, lower linear heat generation rates and relatively high temperatures). Fuel designs will be developed and tested (using ex-pile and in-pile techniques) to the extent that facilities and funds allow.

4.3 Fuel Properties and Performance Data Collection

Objective:

- Accumulation of a fuel properties and performance database and an experience base

The fuel and fuel cycle viability R&D for the LFR is expected to be addressed as part of the Advanced Fuel Cycle Initiative (AFCI). For fuel development, the AFCI, from FY2003-2009 is carrying out "Proof-of-Principle" testing on metal and nitride fuels for fast-spectrum transmutation. This testing includes fabrication development, fuel characterization, and irradiation testing and examination. The goal of the AFC program is to select a reference transmutation fuel by 2009 for further development. The LFR program will use the AFCI results to supply data needs for LFR design, and will input design and data requirements toward the formulation of AFCI fuel R&D plans.

4.4 LFR Fuel Cycles

Objective:

- Establishment of fuel cycle technological and institutional requirements for the LFR
- Initial assessment of fuel cycle technology options and institutional issues for impact on LFR system design

The LFR concept has implications for long-term management of fuel cycles and the institutions that govern them as well as an associated set of fuel cycle technology issues. The LFR program will define the requirements for LFR fuel cycles and then assess the implications of fuel cycle technology options. Consideration will be given to the context of institutions that regulate and manage fuel cycle and nuclear fuel commerce.

5 BUDGET

The known and proposed budget for the LFR R&D described in the previous sections is provided in Table 1.

Table 1 Known and Proposed 10-year Budget for U.S. LFR R&D

Technology	FY 04	FY05	FY06	FY07	FY 08	FY 09	FY 10	TOTAL
System Design & Evaluation								
Materials								
Energy Conversion								
Fuels & Licensing								
Total								

6 MILESTONES

Milestone	Date
FY'04	
LFR 10-Year Program Plan Draft	2/28/04
Deployment and institutional studies w/ report preparation	8/30/04
Licensing and Safety Approach Studies (from FY-03)	12/30/03
Licensing and Safety Approach Document	12/30/03
Status report on deployment and institutional studies	8/30/04
Report on DELTA experiments, operation and corrosion test results	9/15/04
Input to draft LFR Material Selection and Qualification Plan	6/30/04
Prepare coolant technology development plan	6/30/04
FY'05	
Establish point design for subsequent concept development	3/31/05
Issue document of economic requirements and proliferation-resistance principles	8/30/05
FY'06	
Issues design and data needs document	4/30/06
Establish controllable range of oxygen content in lead/LBE	6/30/06
Update Safety and Licensing Approach document	8/30/06
Issue fuel qualification strategy document	8/30/06
FY'07	
Issue report on SCO_2 design requirement for LFR	6/30/07
Issue status report on feasibility of autonomous load following concepts	8/30/07
Submit concept paper on implementation of fuel cycle centers	12/31/06
FY'08	
Establish techniques for lead/LBE chemistry control and flow measurement	8/30/08
Establish reference fuel & cladding type and design for long core lifetime	8/30/08
FY'09	
Complete initial measurements of natural flow properties for lead/LBE	6/30/09
Issue update of economic requirements and proliferation-resistance principles	8/30/09
Issue report on lead/LBE corrosion behavior of LFR materials candidates	8/30/09
FY'10	
Issue handbook of properties data for lead/LBE	3/31/10
Issue handbook of materials properties data for LFR	3/31/10
Establish pre-conceptual design	8/30/10
FY'11	
Issue report on status of mechanistic materials modeling	3/31/11
Issue report on irradiation performance of LFR candidate materials	8/331/11

FY'12	
Establish reference core design parameters	3/31/12
Issue handbook of LFR fuel and cladding properties	6/30/12
FY'13	
Submit status report on LFR conceptual design	8/30/13
Submit status report on LFR licensing basis	8/30/13